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A SIMPLE AND INEXPENSIVE CHRONOSCOPE.

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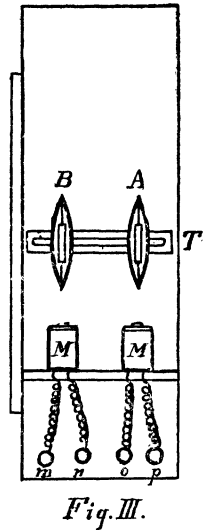
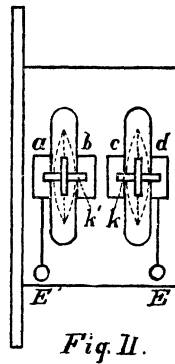
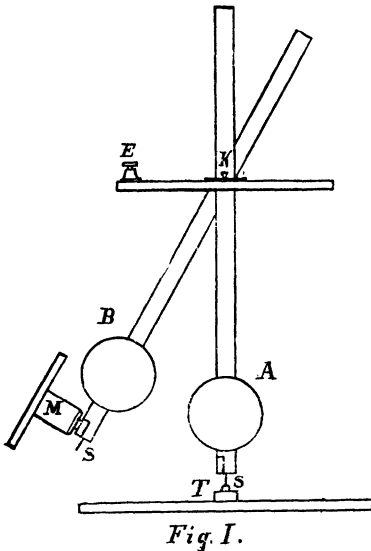
The application of the principle of the vernier to the exact measurement of time was suggested forty years ago by Kaiser, the veteran astronomer of Leyden.¹ From an abstract of one of his papers in an early volume of Carl's *Repertorium für physikalische Technik*, the suggestion here to be developed was received.

In principle, the instrument is as simple as possible—nothing more than two pendulums, one swinging across its arc in a second, the other in a little less or a little more than a second; for example, in ninety-nine hundredths. The more rapid one will then gain on the slower one a hundredth of a second in each swing of the latter, and when they start together will exactly coincide with it at the one-hundredth swing, the two-hundredth swing, and so on. The application of the instrument is equally simple. Required the time that elapses between the beginning and end of some phenomenon—say, the fall of a ball. When the ball starts, the full second pendulum is started; when the ball stops, the more rapid pendulum is started. The latter gains one one-hundredth of a second during each swing of the former, and finally overtakes it. It is, therefore, only necessary to know the number of swings made by the slower pendulum before this happens, to know the number of hundredths of a second intervening between the starting of the two pendulums, or between the beginning and end of the fall of the ball. More explicit examples will be given below.

In the actual construction of such an instrument two points need care; namely, the starting of the pendulums, and the recognition of the swing in which they exactly coincide. The first is rather easily managed, by having the pendulums held at one end of their arc by electromagnets and releasing them by breaking the electric circuit. The other also may be

¹“On a new application of the principle of the nonius to the exact observation of sudden phenomena.” *Tijdschrift voor de Wis- en Natuurkundige Wetenschappen*. Vol. v, 1851. Also applied by him to the measurement of astronomical personal equation: *De volledige bepaling van persoonlijke fouten bij sterrekundige waarnemingen. Verslagen en mededeelingen der akademie der wetenschappen, Amsterdam, Afdeling natuurkunde*, xv, 1863, 173; also in abstract in the *Archives néerlandaises des Sciences*, Harlem, I, 1866, 193.

accomplished by making the two pendulums, when they coincide, complete an electric circuit themselves, in which is placed a telegraph sounder. In the cut below, Fig. I represents the pendulums as seen from in front, pendulum *B* held by its electromagnet, pendulum *A* at rest in its middle position. *T* is a little trough of mercury into which platinum wires *s s*, at the lower end of the two pendulums, dip when the pendulums are in their middle position. From these platinum points wires (not represented in the figure) run up the pendulums to the knife-edges (Fig. I, *k*, Fig. II, *k* and *k'*) on which the pendulums rest. In Fig. II is represented the shelf by which the pendulums are supported. The knife-edges rest upon metal



plates, *a b c d*, fastened to the shelf; and from two of these, *a* and *d*, wires are lead to the binding posts, *E E'*. Now, when the wires of an electric circuit are fastened into these binding posts, the circuit will be complete when the platinum points of both pendulums are in the mercury of the trough, and at all other times will remain broken. When the pendulums are at rest the circuit will be continuously closed. When they are swinging it will be closed (and the sounder will click), as often as both cross the mercury at the same time, either going in the same or in opposite directions; that is, when they coincide or are just halfway between coincidences. Fig. III is a plan of the instrument at a level just above the pendulum bobs (*A* and *B*), showing the electromagnets, *M* and *M*, and the mercury trough, *T*.

The ease with which a tolerably accurate instrument of this kind can be made, and its very small expense, will appear if I describe more fully one recently made here in the carpenter's shop of the physiological department. The framework of the instrument is a pine board a foot wide and about two feet long, kept upright by horizontal pieces nailed to its sides at the bottom. About halfway up, on the face of this board, is fastened a shelf three and a half inches wide, through longitudinal slots in which the pendulums hang. The pendulums, which in this case swing across their arc in approximate half-seconds, instead of whole seconds as in the example above, are about 20 inches long. Their rods are pine slats about seven eighths of an inch wide and three sixteenths of an inch thick. The knife-edges, which are put through the slats a little above their middle, were made by filing bits of eighth of an inch iron wire into triangular shape; and to hold them in place, they are soldered to little bands of tin that encircle the pendulum rods just above them. The plates on which the knife-edges rest are small pieces of sheet brass screwed to the wooden shelf, and have shallow notches filed in them to keep the knife-edges from getting out of place in the ordinary handling of the pendulums. The pendulum bobs are made of sheet lead, several thicknesses being cut in oval form and bent around the rods and their edges caught together with solder. They weigh not far from three quarters of a pound apiece. They were made so as to slip tightly upon the rods till a coarse adjustment could be made, and then were fixed in place by driving a headless pin through each. The electromagnets, the two bobbins of such a magnet as is used in ordinary telegraph sounders, were screwed to a bit of wood and fastened at the proper angle to the back piece of the instrument and to one of the side pieces that keep the latter erect. The mercury trough was made by filing a groove about an eighth of an inch wide and an eighth of an inch deep in a small piece of hard rubber, and damming up the ends with sealing wax. This trough was further fixed with sealing wax in a shallow china dish to catch any mercury that might be spilled, and the whole was adjusted by hand, so that the platinum points rested in the middle of the mercury when the pendulums were at rest. The electromagnets and six binding posts can be bought ready-made for one dollar and sixty cents respectively; a quarter's worth of sheet lead is ample; the bits of brass, the hard rubber for the mercury trough, the platinum wires, the boards for the frame, etc., etc., together should not cost more than a dollar—a total of two dollars and eighty-five cents. While this instrument was not carelessly made, it lacks, as appears from the above description, the fine adjustments

and many of the conveniences that could readily be supplied by an experienced mechanic, and, in especial, it lacks the permanency of adjustment that an instrument so made would certainly possess.

The regulation of the instrument is an important and somewhat tedious matter, but not a difficult one. In our instrument the pendulums will continue to swing long enough to be counted for several minutes. If one is at rest with its point in the mercury, the other will make and break circuit at every swing, that is every half-second, and its vibrations may be counted from the clicks of the sounder, a process which practice considerably facilitates. If the observer follows the pendulum with his eye he finds the task a little easier—at least it seems so to the writer—and he has the further advantage of a constant check on his counting in the fact that the pendulum moves one way for all odd numbers and the other way for all even numbers. To find the rate of the pendulum, the observer listens to the clicks of the sounder, following at the same time the second hand of his watch till it marks a division simultaneously with a click, counts that naught, the next click one, and so on for five minutes or more as he desires, and thus discovers how nearly his pendulum makes the required number of swings. In this way it is not difficult to get the number to a single vibration. The following are the results of several such counts, on the slower pendulum of our instrument, made at one sitting.¹

Count by	half-seconds for	9 minutes:	1082	against	1080	required.
"	whole seconds "	10 "	602	"	600	"
"	half-seconds "	9 "	1082	"	1080	"
"	whole seconds "	10 "	601½	"	600	"
"	half-seconds "	10 "	1203	"	1200	"
"	whole seconds "	9½ "	572	"	570	"

It will probably be found convenient to leave the pendulum with a small error, and make a numerical correction, if necessary, in the final results.

Having fixed the rate of the full time pendulum, a more rapid way is open for the setting of the other. After a coarse adjustment by counting, the two magnets may be brought

¹ The pendulum completes a vibration in a slightly shorter period as its arc grows smaller; measurements made on the slower pendulum with the tuning-fork (though on another occasion, when a single count showed the rate of the pendulum itself a trifle slower) gave the following values in thousandths of a second as the time of a double vibration; At the start, 1000.9; after five minutes, 998.4; after nine minutes, 996.5 If we assume that this increasing loss is equivalent to a shortening of each of the six hundred double vibrations by an amount equal to the loss shown after five minutes, we get something over one and a half as the number of vibrations gained by the pendulum upon itself in ten minutes.

into one electric circuit, and the two pendulums released at the same instant by the breaking of that circuit. The swings of the slower pendulum may now be counted till the two are exactly in opposition (halfway to a coincidence), which should occur, if the rapid pendulum is nearly right, after about one hundred half-seconds ; or, if one prefers, the count may be carried on to a coincidence which should occur after about 200 half-seconds. The error is thus found by counting one or two hundred instead of five hundred or a thousand. A very little change in the pendulums shows itself at once in the number upon which the opposition or coincidence occurs ; a difference of one ten-thousandth of a second in each vibration, amounting to one one-hundredth of a second in one hundred vibrations, will make a difference of one in the number of the vibration in which the opposition or coincidence occurs. Indeed, the required change of adjustment is often so minute that it is convenient, as before, to leave a small error for numerical correction. The difference between tables *A* and *B*, below, are probably due to small accidental disturbances of adjustment or to spontaneous changes in the materials of the instrument ; and even larger differences have sometimes been found, but so long as the rate remains constant during a series of experiments, accurate results can be obtained by correction, even from such a machine as the one above described.¹

A.—Table showing numbers (half-seconds) on which occurred the clicks marking opposition and coincidence.

April 8.		Opposition.		Coincidence.			
99	100	101	199	200	201		
	100	101		200	201		
	100	101		200	201		
	100	101					
99	100	101		200	201	202	
	100	101		200(?)	201	202	
	100	101			201	202	203
	100	101			201	202	
	100	101	102(?)	200	201	202	
	100	101			201	202	

¹ As these tables show, the clicks do not indicate a single swing of the pendulum, as that to which the opposition or coincidence belongs, but two at least, and sometimes three. This, however, is not a serious disadvantage ; for if three are indicated, the opposition or coincidence falls most nearly on the middle one of the three, or if two, between them. Indeed, it is sometimes possible to tell from the different intensity of the two clicks, which stands nearest to the exact opposition or coincidence.

B.—Table showing numbers (half-seconds) on which occurred the clicks marking opposition.

April 12.

First Series : Opposition.			Second Series : Opposition.			
	101	102	103	100	101	102
	101	102	103(?)		101	102
	101	102			101	102
	101	102			101	102
100	101	102			101	102
	101	102				
100	101	102				
100	101	102				
100	101	102				
100	101	102				
100(?)	101	102	103(?)			

Another possible error, and one of a most serious kind, is introduced if one of the magnets holds its pendulum longer than the other after the breaking of the circuit, which is especially likely to happen if the cores of the magnets are allowed to become permanently magnetic. To prevent this, in using our instrument, a commutator has been put into both circuits, and the direction of the current changed at each test¹. Fortunately, the instrument itself affords a means of detecting this error, if it amounts to more than four or five thousandths of a second. Assuming that the speed of the pendulums at the start is such that the breadth of the trough of mercury is represented by .007 sec., there will be a click from the sounder every time that one pendulum is within .007 sec. of the other, as the two cross their middle position². Under these circumstances, three things may happen when the pendulums start at or near the same instant. (a) If the rapid pendulum starts more than .0045 sec. ahead of the slow one, and gains on the slow one (as it does), one quarter of a hundredth of a second in the quarter second before it reaches the mercury, it will be clear of the mercury before the slow pendulum enters it, and there will be no click of the sounder. (b) If the slow pendulum starts even as little as .0005 sec. ahead of the rapid one, the latter will only be .002 sec. ahead when both cross the mercury, and there will be a click of the sounder, and again when the pendulums come to the mercury on the return swing, the more rapid one having gained half of a hundredth of a second more, it will

¹ If such an error were present, it might be balanced in the result by interchanging the pendulums, so that the error should affect one for the first half of the series of measurements, and the other for the second half.

² This seems a fair assumption, for if the pendulums cause a click when separated by .007 sec., a coincidence would always be marked by two clicks and might be marked by three, a condition of things which the tables already given show to happen after the pendulums have already swung fifty or one hundred seconds.

be but .007 sec. ahead, and will cause a second click. (c) When the rapid pendulum has less of a start than .0045 sec., or the slow one less of a start than .0005 sec., there will be a single click as they cross the mercury, and no second click till they reach opposition.

To test the accuracy of the instrument in actual measurements, it was used to measure the time of the falling of the ball in the apparatus ordinarily used for regulating the Hipp chronoscope, the apparatus having been fixed to break a second circuit instead of closing the first, as in the common arrangement. The calculated time for the fall of the ball *in vacuo* was 319.28 thousandths of a second. The average of fourteen measurements taken with a vibrator making sixty vibrations a second, gave the actual time as 331.2 thousandths of a second. Ten measurements with the pendulums (counting half-seconds) gave the following as the numbers of the swings upon which the clicks of the sounder indicating a coincidence occurred :—

April 12.	67(?)	68	69	67	68	69	
	67(?)	68	69	67	68	69	
	67	68	69	67	68	69	70(??)
	67	68	69	67	68	69	
		68	69	67	68	69	

Neglecting the doubtful numbers (for which the click was very faint, if there was any at all), the average number for the coincidence is 68.15. These, however, are half-seconds; the number of seconds (and the corresponding number of hundredths of a second) is 34.075, or, in thousandths of a second, 340.75. This first result is, however, subject to correction. In the first place, each swing is counted when the pendulum is in the middle position, while the start is made from an extremity of the arc; a quarter of the gain of a double swing, *i. e.*, .0025, is therefore to be added to the above result, making 343.25. In the next place, the rapid pendulum did not at this adjustment of the instrument reach an opposition at 100 half-seconds, but on the average at 101.3 (see table *B* above). Each one of the 68.15 half-second swings enumerated, therefore, represents, not $\frac{1}{100}$, but $\frac{1}{101.3}$ of a swing of the slow pendulum. Reducing, accordingly, to an exact adjustment gives 67.28 half-seconds and 33.64 hundredths of a second, to which, when .0025 is added, as before, a final result is reached of 338.9 thousandths of a second—7.7 thousandths of a second in excess of the result obtained with the vibrator. No correction is here applied for error of the slower pendulum, which on this occasion is believed to have been insignificant. In two other series of measurements made at another time, one of 10 and the other of 25 trials, the coincidence fell between 67 and 68 seven times, on 68 once, between 68 and

69 twenty-four times, between 70 and 71 twice, and between 72 and 73 once, the amount of the last three being not impossibly connected with irregularities in the fall apparatus itself.

A better made instrument might give better results, but the accuracy attainable with this is sufficient for the demonstration of nearly all the more important facts of simple reaction-times, and abundantly so for the longer and more complicated reactions with discrimination and choice and for association-times, where the average variation of the single tests in a series may itself amount to a tenth of a second or more. For many of these purposes, a pair of pendulums adjusted to measure twenty-fifths of a second would answer well enough, and the regulating of them and the counting at each observation would take but one fourth the time. The instrument has two advantages aside from its simplicity and cheapness. It is silent in its operation, and so may be used in taking reaction-times in the immediate presence of the subject. And it is well suited to lecture demonstrations, for a whole roomful can easily see that one pendulum starts before the other, and can count the swings to a coincidence, to all intents taking part in the observation themselves. The instrument (in the absence of any other name, why not call it a *time-vernier*?) would be greatly improved by adding a dial and second hand, so as to make the counting automatic, and probably also by swinging the pendulums between points instead of on knife-edges. Care in keeping the mercury clean and the contact good at the knife-edges is, of course, essential to a satisfactory functioning of the instrument.